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RESEARCH MEMORANDUM

PRELIMINARY INVESTIGATION OF THE FAILURE OF

PRESSURIZED STIFFENED CYLINDERS

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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PRELIMINARY INVESTIGATION OF THE FAILURE OF PRESSURIZED STIFFENED CYLINDERS

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SUMMARY

Tests were made of stiffened cylinders of 2024 (formerly 24S) aluminum alloy under internal pressure and cyclic torsion. Both gradual and explosive types of failures occurred. The type of failure depended upon the hoop stress and structural configuration, and particularly upon the ratio of area in rings to associated skin area.

INTRODUCTION

Failures of pressurized fuselages that have occurred have varied in character from rather minor rupture to catastrophic explosion (ref. 1). The question naturally arises as to whether the character of the failure can be controlled by selection of materials or structural proportions. Accordingly, the factors which influence the character of the failure are being investigated in the Langley structures research laboratory. Various materials, structural configurations, and loading conditions are being tested in an effort to determine which are conducive to mild failure on the one hand and to explosive failure on the other. This paper reports the results of the tests on the first eight cylinders, all of which were constructed of 2024 aluminum alloy, in the proportions and subjected to the test conditions herein described.

SYMBOLS

$A_{R_{full}}$ cross-sectional area of ring, in.^{2}

$A_{R_{red}}$ minimum cross-sectional area of ring (cross section at notch for longitudinal), in.^{2}

l ring spacing, in.

p internal pressure, ksig

r radius of cylinder, in.

t_S skin thickness, in.

δ crack length, in.

δ_{cr} maximum length of crack that can be tolerated before explosive failure of cylinder occurs, in.

σ tensile stress, ksi

σ_{hoop} simple hoop-tension stress in skin, pr/t_S, ksi

σ_{tu} ultimate tensile strength of material, ksi

TEST SPECIMENS

The test specimens (fig. 1) are approximately representative of 1/4-scale models of fuselage construction. Internal reinforcing members are identical in all cylinders, consisting of longitudinal stringers and rings riveted to the skin between longitudinals. The rings are 0.051-inch spun Z-sections $1\frac{1}{4}$ inches deep, notched for the 20 longitudinals so that the full cross-sectional area $A_{R_{full}}$ of 0.093 square inch is reduced to a value of $A_{R_{red}}$ of 0.053 square inch. The longitudinals are 0.040-inch-thick extruded Z-sections having a web width-thickness ratio of $12\frac{1}{2}$ and a ratio of outstanding flange width to web height of 0.4. The cross-sectional area of the longitudinals is 0.045 square inch. All internal material is 2024-T4 (formerly 24S-T4) aluminum alloy.

Five gages of 2024-T3 (formerly 24S-T3) skin - namely, 0.012, 0.016, 0.025, 0.032, and 0.040 inch - have been tested. These five skin gages together with the use of two ring spacings - 7.5 and 15 inches - have made up the primary variations in structural configuration so far investigated. The combinations of these variables used are listed in table 1.

A secondary structural variation has been the cutout in the center of the cylinder used as a stress-raiser to induce a fatigue crack in the cylinder. For some of the cylinders subjected to the high values of hoop tension, a 2-inch-diameter circular cutout has been used. For the lower stresses, a square cutout with 1/4-inch corner radius is used to increase the stress concentration and reduce the number of load cycles required to cause cracking. Reinforcing around the cutout, consisting of a flange angle around the perimeter of the hole and a floating diaphragm to close the hole, was riveted on the first cylinder and was bolted with oversize holes on all subsequent cylinders.

All riveting was made with 3/32-inch-diameter 2117-T4 (formerly A17S-T4) aluminum-alloy round-head rivets (AN430AD) at approximately 1/2-inch pitch. Seams between sheets forming the skin were longitudinal lap joints with two rows of rivets. In addition to the double rows of rivets, Araldite cement was used in all of the skin seams (and only in the skin seams) in an effort to avoid seam failures.

TEST PROCEDURE

The tests were made in the combined-load testing machine of the Langley structures research laboratory as shown in figure 2.

Internal pressure, supplied by oil from the hydraulic pumping unit shown in the lower right of figure 2, is held constant throughout each test to give the desired value of hoop tension. A cycling device, similar to that described in reference 2, fitted to the torsion loading component applies cyclic shear to the cylinder. Thus, stress conditions are induced adjacent to the cutout not too dissimilar from those adjacent to a cutout in the side of a pressurized cabin in flight, except that in the test specimen the magnitude of the shear is exaggerated in order to reduce the number of cycles to failure.

The test procedure in each case is to increase the internal pressure until the desired nominal hoop-tension stress is attained, simultaneously operating the axial loading component to keep the external axial load on the cylinder at zero. Cyclic torsion is then applied until a crack opens at the cutout. The rate of cycling is then somewhat reduced and the internal-pressure valves and pumping rate are continously adjusted to maintain the desired internal pressure despite growing leakage through the crack. Cycling is continued until the crack is so large (approximately 2 inches long) that pressure can not be maintained within the available pumping capacity of approximately 10 gallons per minute.

RESULTS

The results are presented in the last three columns of table 1. Two distinct modes of failure occur: one is characterized by a gradual crack growth (see fig. 3); the other can only be described as an explosive failure in which the crack opens suddenly over more than one bay width, failing the internal ring at one of its 20 notches (see fig. 4), or tearing the skin away from the ring.

The hoop stress level is not the sole cause of the difference between the modes of failure. In fact, specimen 4 had a gradual crack growth at a higher stress level (30 ksi) than that for specimen 3 (20 ksi) which had an explosive failure.

The number of torsion-load cycles between initial cracking and explosive failure is generally small, whereas a somewhat larger number of additional load cycles may be required after crack initiation in cases of gradual failure to open the crack sufficiently to necessitate cessation of the test. Exceptions to this general rule are cylinders 5 and 7, which failed gradually at hoop stresses of 10 ksi and 20 ksi, respectively. In these cases, only about 50 additional load cycles were required to propagate the crack to such an extent that pressure could not be maintained. Because the rate of crack growth in cylinders 5 and 7 in terms of number of load applications was similar to that in cylinder 6, the possibility exists that a similar type of failure (explosive) also might have been encountered in these two cylinders if somewhat greater pumping capacity had been available to permit continuation of the test.

DISCUSSION

Because the radius-to-thickness ratio r/t_S is generally large for fuselage construction, the failure of pressure cylinders representative of fuselage construction can perhaps be considered similar to that of cylinders of infinite r/t_S. Accordingly for unstiffened cylinders, a curve should exist, similar in character to that for flat sheet of figure 8 of reference 3, relating the hoop tensile stress σ_{hoop} to cause explosive-type failure to a critical crack length δ_{cr}. A portion of such a curve derived from figure 6 of reference 4 is presented in figure 5.

For stiffened cylinders, the critical crack length may reasonably be expected to be greater than that for unstiffened cylinders. In fact (again for $r/t_S \rightarrow \infty$), if the ring area in the stiffened cylinder is great enough to carry the hoop-tension load, the cylinder could perhaps be cracked along its entire length without encountering an explosive failure. Thus, on a plot similar to figure 5, the critical crack length for stiffened cylinders may vary from zero at a hoop stress equal to 75 percent of the tensile ultimate σ_{tu} of the material as found for 2024-T3 aluminum alloy in reference 4 (since, as can readily be determined from ref. 5, the circumferential stress midway between rings is usually very nearly equal to the simple hoop tension) to a length equal to the ring spacing at the stress found from

$$\frac{prl}{A_{R_{red}}} = \sigma_{tu} \tag{1}$$

or for 2024-T3 for which $\sigma_{tu} \approx 70$ ksi,

$$\frac{pr}{t_S} = 70 \frac{A_{R_{red}}}{lt_S} = \sigma_{hoop} \tag{2}$$

where

p internal pressure, ksig

r radius of cylinder, in.

l ring spacing, in.

$A_{R_{red}}$ minimum cross-sectional area of ring, in.^{2}

σ_{hoop} hoop tension stress, ksi

If a linear variation with stress from $\delta_{cr}/t_S = 0$ to $\delta_{cr}/t_S = l/t_S$ is assumed (fig. 6), the critical crack length depends directly upon the reinforcement ratio, that is, the ratio of cross-sectional area in the rings $A_{R_{red}}$ to the associated skin area lt_S. Thus, as might be expected, the critical crack length at a given hoop stress is longer for a large value of $A_{R_{red}}/lt_S$ than for a small value of the reinforcement ratio.

Because this analysis is oversimplified, the plotted straight-line relationships of figure 6 for critical crack length should perhaps be regarded as upper limit or maximum values which can seldom practicably be achieved, and, accordingly, these curves do not provide a suitable criterion from which it can be determined whether a cylinder is prone to explosive failure. Such factors as bulging of the skin between rings and local stress concentrations probably tend to reduce the length of crack that can be tolerated below that given by the straight-line relationship of figure 6 (though not below that corresponding to the unstiffened cylinder). A rigorous analysis of the stress distribution along the cracked skin, or adequate test data, is required to establish a critical-crack-length criterion which is surely not unconservative.

A more conservative criterion is given by the end points of figure 6, that is, for the ratio of critical crack length to ring spacing of one. These end points represent rings of cross section heavy enough to carry the entire hoop-tension load by themselves with the skin cracked over the full bay length.

A plot of these end points (the straight line in fig. 7) as given by equation (2) may perhaps be worth investigation as a gross kind of criterion for a boundary (which should tend to be conservative particularly at low stresses) between regions of slow and explosive crack propagation in the skin of stiffened pressurized cylinders. The present test data, plotted in figure 7, substantiate to some extent the conservatism of this criterion. The open points $\times$, $\curlywedge$, and $+$, representative of the explosive failures, fall above the line which represents the ring area required at any hoop tension to carry the entire hoop-tension load with the skin cracked along the entire bay length. The closed points $\bigcirc$, $\square$, $\diamond$, and ∇, representative of the specimens in which the crack grew gradually, fall below or not far above the straight line. Thus, the data tend to confirm that for the type of construction tested this boundary is somewhat conservative.

The type of boundary given in figure 7 is probably too conservative at the low stress levels which correspond to the stresses required for explosion of an unstiffened cylinder. Data to establish quantitatively, for low stresses and large width-thickness ratios, curves like that of figure 5 would be of assistance in the evaluation of the type of failure to be expected in this low stress region.

CONCLUDING REMARKS

Tests on pressurized stiffened cylinders of 2024 (formerly 24S) aluminum alloy have shown that if a crack is opened in the skin it may grow in either a gradual or explosive manner depending upon the structural configuration as well as upon the stress conditions. An important factor in the determination of the type of failure appears to be the reinforcement ratio - the ratio of area in rings to associated skin area. For the type of construction tested, the reinforcement ratio has been shown to provide an approximate conservative criterion of the type of failure although it is perhaps unduly conservative in the low stress region. Additional data are needed to evaluate this region more exactly and to determine the usefulness of the reinforcement ratio as a criterion of gradual or explosive failure for other materials and detailed cylinder design.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., April 13, 1955.

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TABLE 1

STRUCTURAL CONFIGURATIONS, LOADING CONDITIONS, AND RESULTS

Specimen	Cutout	Applied cyclic shear stress, ksi	Skin gage, t_s, in.	Ring spacing, l, in.	$\frac{A_{R_{red}}}{l t_s}$	Hoop tension stress, σ_{hoop}, ksi	Number of cycles to initiate crack	Number of cycles at end of test	Type of failure
1	Square	14.1	0.040	15.0	0.09	20	1,261	1,263	Explosive[a]
2	Square	12.1	.012	7.5	.59	20	281	528	Gradual
3	Square	14.1	.040	15.0	.09	20	136	147.5	Explosive
4	Round	12.1	.012	7.5	.59	30	658	875	Gradual
5	Square	12.1	.040	15.0	.09	10	203.5	255.5	Gradual
6	Round	12.1	.016	7.5	.44	40	728	788	Explosive[b]
7	Square	12.1	.032	7.5	.22	22.5	194	234	Gradual
8	Square	12.1	.025	7.5	.28	30	5	13	Explosive

[a]The first cylinder failed in the seam between two pieces of skin.

[b]The sixth cylinder exploded after the crack had grown gradually to a length of approximately $1\frac{1}{2}$ inches.

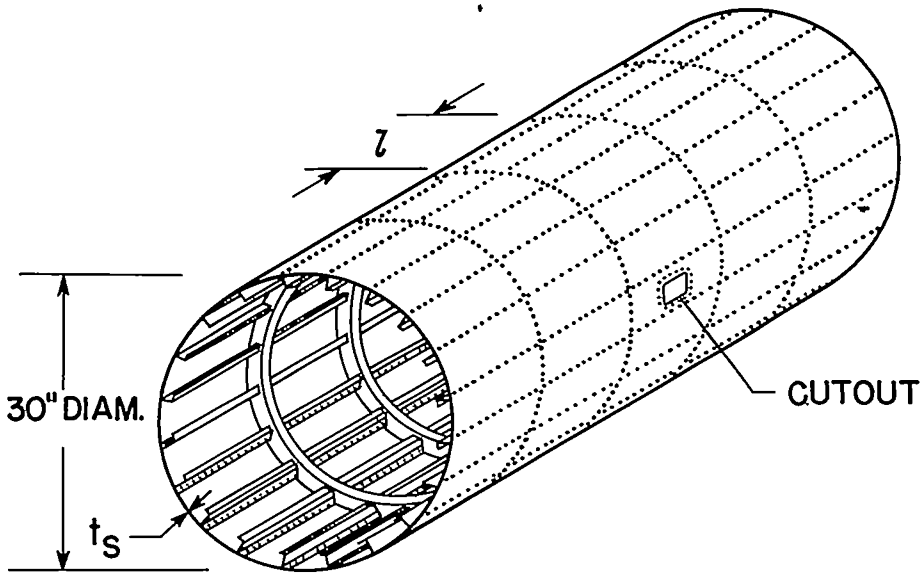

Figure 1.- Pressurized cylinder specimens.

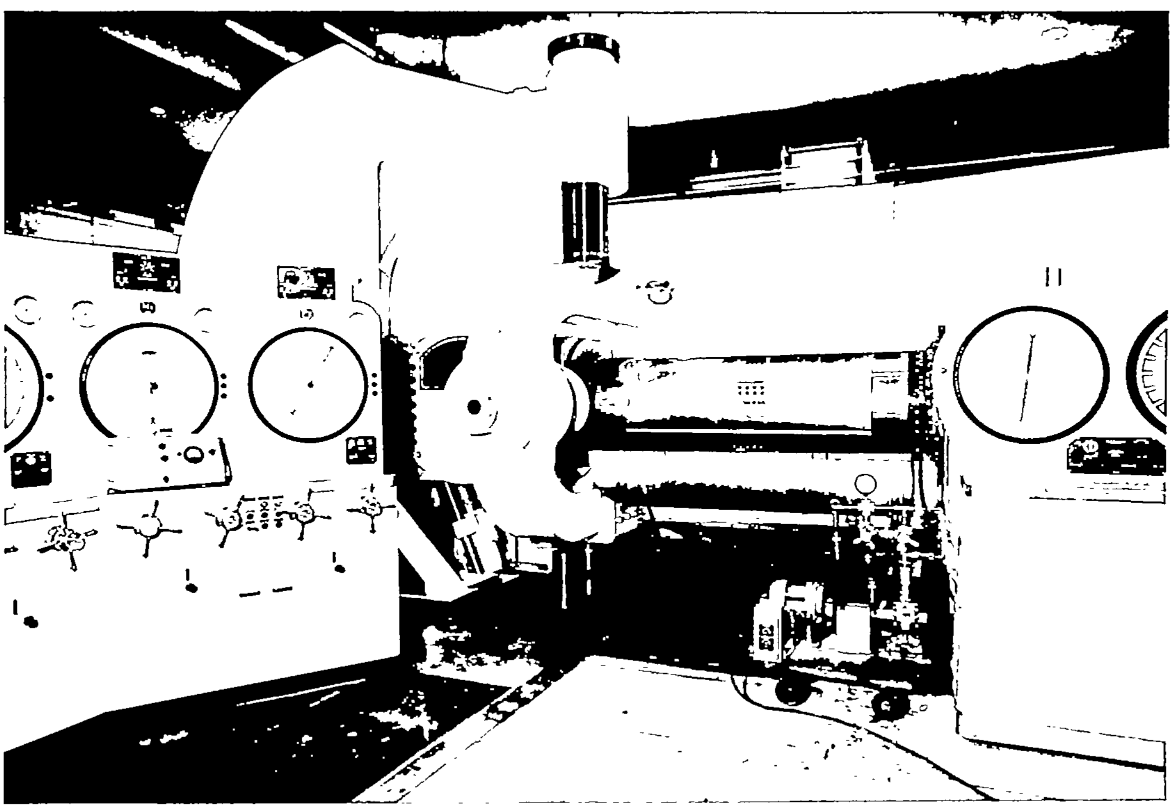

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Figure 2.- Pressurized cylinder test setup.

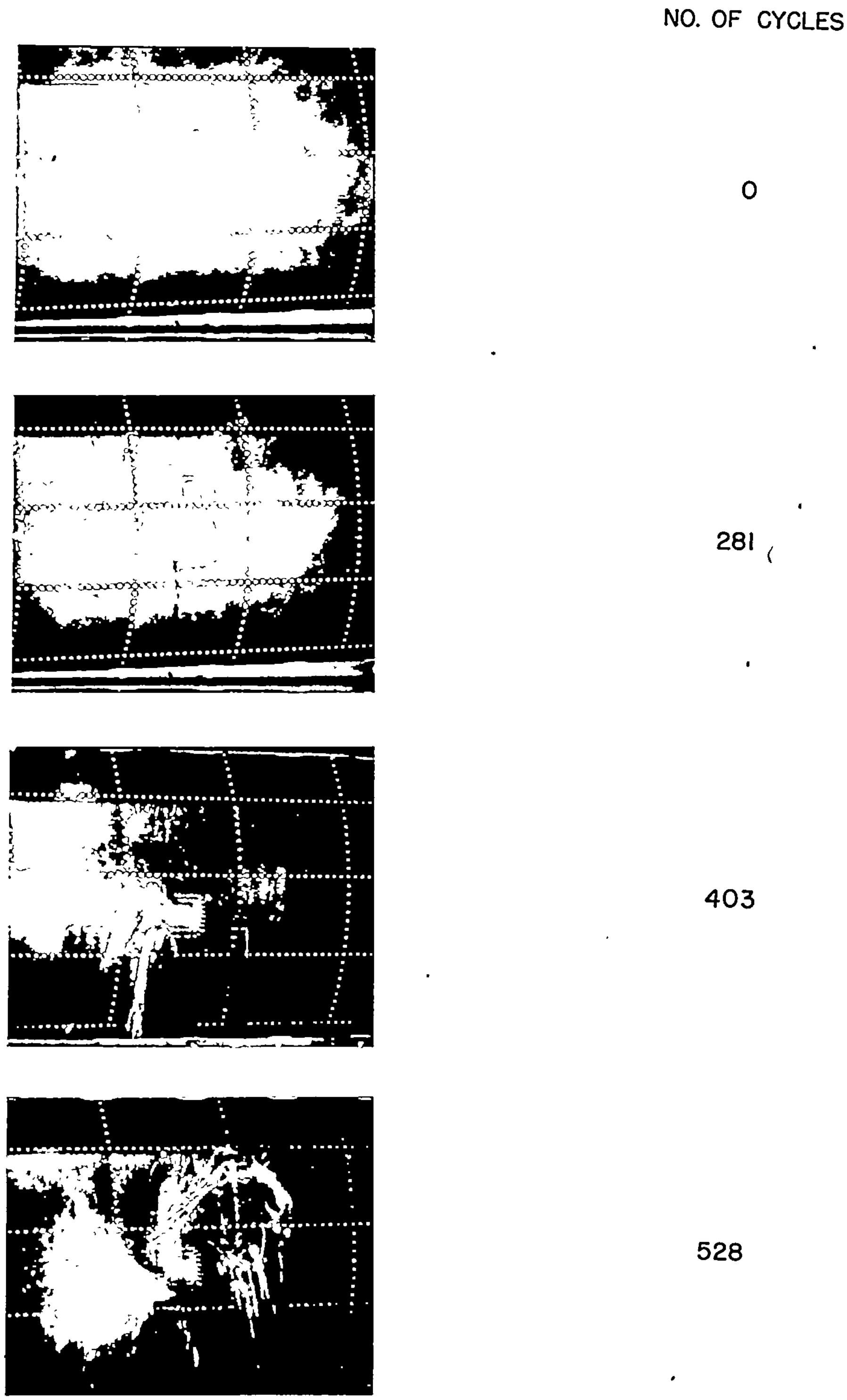

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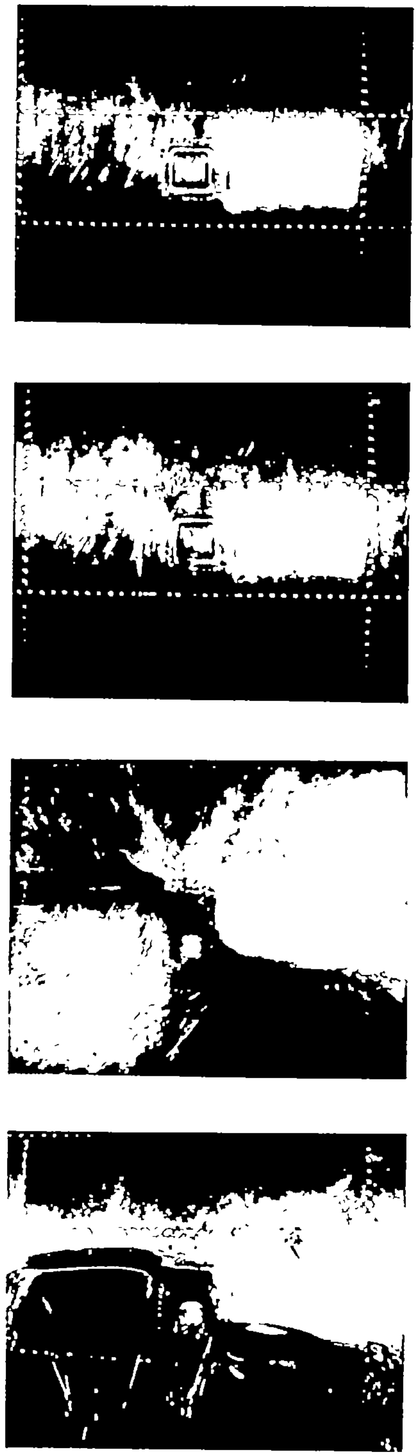
Figure 3.- Failure by gradual crack growth of cylinder 2.

NO. OF CYCLES



136

146

147.5

147.5

L-87950

Figure 4.- Explosive failure of cylinder 3.

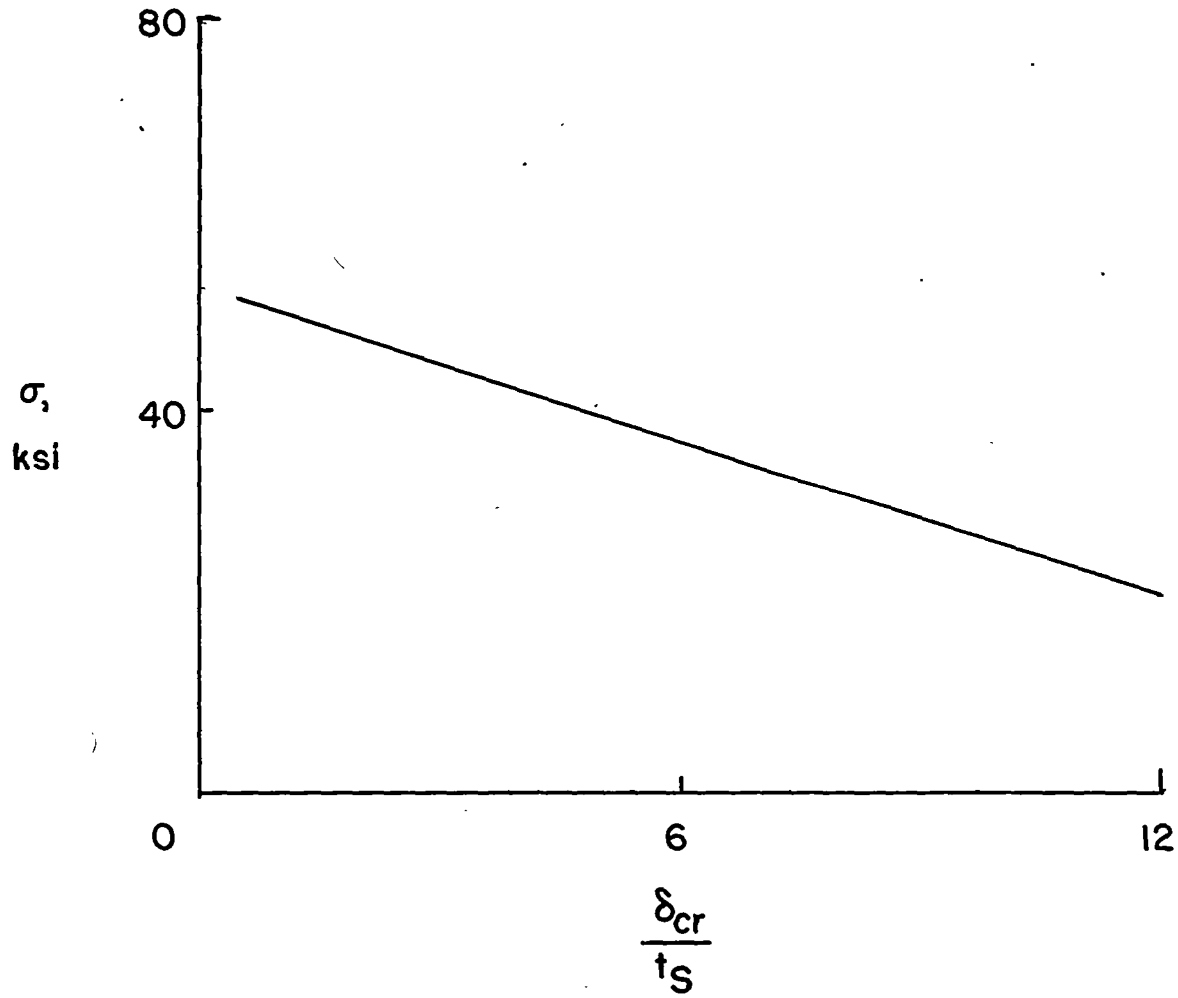


Figure 5.- Relationship between tensile stress and critical crack length for 2024-T3 (formerly 24S-T3) flat sheet of width-thickness ratio of 20 (from ref. 4).

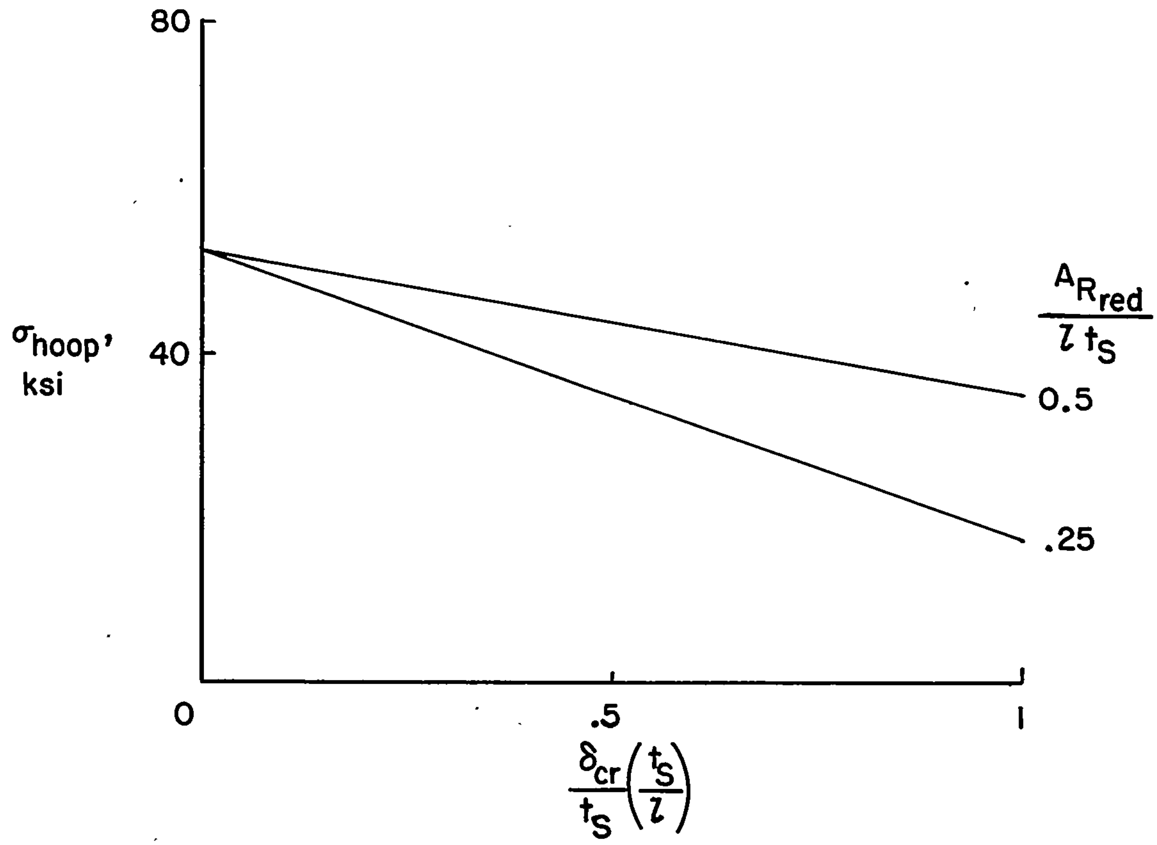


Figure 6.- Simplified relationship between hoop tension and critical crack length for 2024-T3 aluminum-alloy stiffened cylinders.